III.E.3 Advanced Control Modules for Hybrid Fuel Cell/Gas Turbine Power Plants

Objectives

The overall project goal is to develop advanced and intelligent control algorithms for hybrid fuel cell/gas turbine (FC/T) power plants. The specific objectives are:

- Establish a dynamic modeling environment to facilitate simulation studies, as well as development and testing of control algorithms.
- Increase reliability and availability to extend service life of the components in the hybrid FC/T power plant.
- Develop robust controllers that maintain stable operation and high performance in the presence of disturbances.
- Develop optimal control strategies to improve performance and to accommodate fast response during rapid transients.
- Accommodate measurement errors, as well as sensor and actuator faults to reduce the number of unplanned shutdowns.
- Integrate robust and optimal controllers into an overall supervisory framework.

Accomplishments

- Completed development of modular dynamic models for internally reforming carbonate fuel cell (Direct FuelCell®, DFC®) and solid oxide fuel cell (SOFC) as well as balance-of-plant equipment including a micro-turbine generator. The models were based on the MATLAB®/ Simulink® programming environment.
- Completed integration of sub-MW hybrid DFC/T® and SOFC/T simulation programs.
- Developed control strategies for fuel cell stack temperature, gas turbine operation, and fuel feed rate during start-up and power ramps.
- Completed input/output pairing ensuring stable plant operation and minimal interactions among control loops.
- Designed and validated decentralized multi-loop feedforward/feedback control structure.
- Completed off-line optimization studies for eighteen ramp and step load profiles while maximizing efficiency.
- Developed an inferential control strategy for adjusting fuel flow rate via estimation of disturbances in fuel composition.

Hossein Ghezel-Ayagh (Primary Contact),
S. Tobias Junker
FuelCell Energy, Inc.
3 Great Pasture Road
Danbury, CT 06813
Phone: (203) 825-6048; Fax: (203) 825-6273
E-mail: hghezel@fce.com

DOE Project Manager: Magda Rivera
Phone: (304) 285-1359
E-Mail: Magda.Rivera@netl.doe.gov

Subcontractors:
National Fuel Cell Research Center (NFCRC), Irvine, CA
Carnegie Mellon University (CMU), Pittsburgh, PA
Pennsylvania State University (PSU), State College, PA

Introduction

The control system for Fuel Cell/Turbine hybrid power plants plays an important role in achieving synergistic operation of subsystems, improving reliability of operation, and reducing frequency of maintenance and downtime. The control strategy plays a significant role in system stability and performance as well as ensuring the protection of equipment for maximum plant life. Figure 1 shows a simplified process diagram of an internally reforming SOFC/T system, which is being studied for development of advanced control algorithms. The system is based on an indirectly heated Brayton cycle. The anode exhaust, which contains unreacted fuel, is mixed with the cathode exhaust in a catalytic oxidizer, where oxidation of fuel is completed. The oxidizer exhaust passes through a heat recovery unit in which it preheats the compressed air before entering the turbine. The hot compressed air is expanded through the turbine section, driving an electric generator.

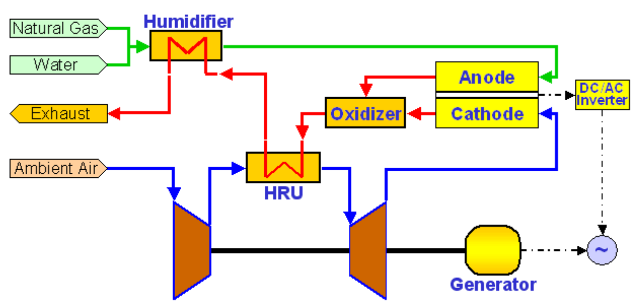

FIGURE 1. Conceptual Process Flow Diagram for the SOFC/T System

Dynamic simulation has proven to be a powerful design tool to study the transient behavior of fuel cell/gas turbine hybrid systems. Development of an advanced control strategy is facilitated by using a dynamic model both as a simulation test bed and as part of the controller itself. Components of the advanced control module include a neural network supervisor, robust feedback controllers, and predictive system models. These advanced control components are used in the development and demonstration of an innovative algorithm that optimally and robustly controls hybrid power systems. The algorithm can easily be adapted to the type of fuel used, whether natural gas, coal gas, or digester gas.

Approach

The advanced control module shown in Figure 2 is based on a feedforward/feedback structure. It consists of a combined robust controller and a neural network supervisor that together manipulate the actuators to optimally control the hybrid system during load ramps. The feedforward controller will provide optimal dynamic scheduling based on the prescribed load profile and trends. Because the optimization routines are computationally too intensive for real-time application, they are carried out off-line. The resulting data is then used to train a neural network supervisor. The feedforward controller performance depends strongly on the accuracy of the model employed to tune it. A feedback control strategy is utilized to compensate for setpoint deviations caused by imperfect feedforward control moves and to counteract process disturbances such as variations in fuel composition and ambient temperature. The feedback controller will be designed to be robust to modeling errors and process disturbances.

Results

Integrated system dynamic models were developed for both SOFC/T and DFC/T systems based on the principles of conservation of mass and energy. The architecture of the computer models in MATLAB/Simulink allows for flexibility in development of integrated system models via interconnection of component models. The dynamic model of the integrated SOFC/T system was utilized to investigate improvements in control strategies related to the operation of the power plant. The study resulted in simple and cost effective approaches for operation of the SOFC/T system over a wide range of power output. The addition of supplementary fuel to the oxidizer and deployment of micro-turbines with variable speed capabilities were shown to be among the preferred thermal management strategies.

Analyses of the relative gain array of the system at several operating points have given insight into input/output pairing for decentralized control [1]. To control the stack temperature during transient load changes, a cascade control structure was developed to accommodate the large time constant of the fuel cell stack in rapid load following applications. Inferential sensing of the fuel composition was implemented using voltage as an indicator of varying fuel concentrations. This algorithm was implemented to manipulate the fuel flow, which resulted in making SOFC/T systems robust to varying fuel compositions.

The resulting system control approach is shown to have transient load-following capability over a wide range of power, ambient temperature, and fuel concentration variations. The results in Figure 3 demonstrate the robustness to ambient temperature variation by maintaining both fuel cell temperature and system power close to their setpoints.

A nonlinear programming framework has been developed to determine optimal operating policies for hybrid FC/T power systems. The approach consists

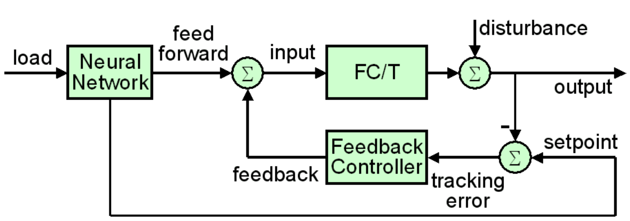

FIGURE 2. Advanced Control Module Comprising the Neural Network Supervisor and Robust Feedback Controller

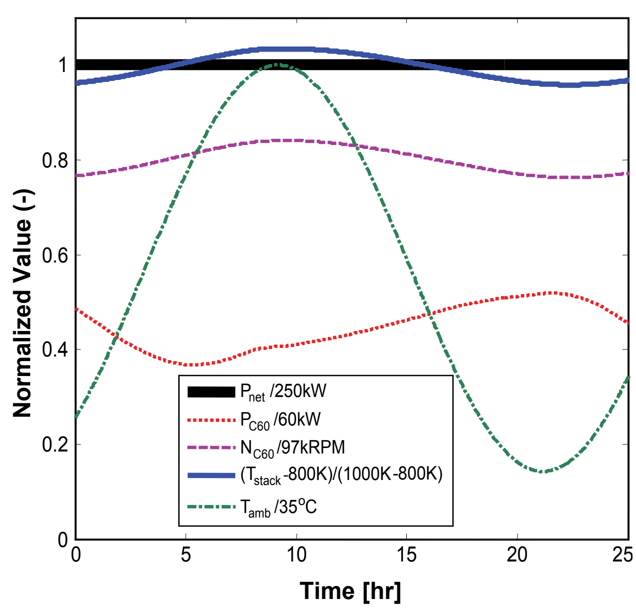

FIGURE 3. Controlled System Response to a Diurnal Ambient Temperature Variation from 5°C to 35°C

of a dynamic model of the system, reformulated as a set of index 1 differential algebraic equations [2]. The system model was discretized with an implicit Runge-Kutta method and formulated in the AMPL modeling environment. This allowed for the straightforward solution of a dynamic optimization problem using large-scale nonlinear programming solvers; the IPOPT solver was used for this project [3]. The computer model was utilized in the optimization of operating trajectories, including ramping the entire power range at various speeds as well as local stepping studies at various power levels. Optimization studies were performed and feedforward control moves and setpoints were provided to Matlab/Simulink to visualize and interpret the results. Eighteen case studies showed that the dynamic optimization could be performed quickly with excellent results.

The optimization problem was augmented by an efficiency measure. Because of its built-in flexibility, the program was easily adapted to maximize efficiency. The ramping and stepping studies were repeated, with higher efficiencies achieved while tracking the desired profiles. Results show that it is possible to operate the power plant as desired while simultaneously enhancing efficiency. Figure 4 shows the achieved efficiency improvement for a load stepping study by comparing the results with and without the inclusion of the efficiency measures in the optimization's objective function.

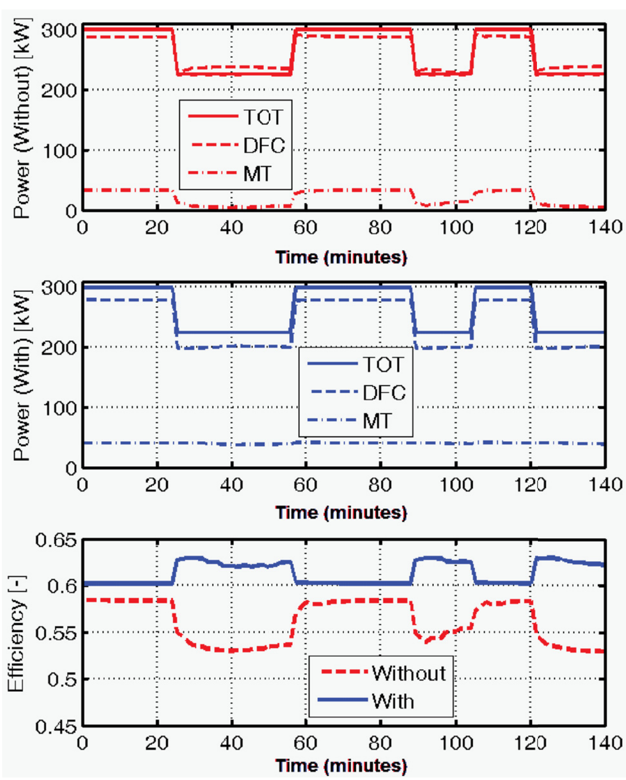

FIGURE 4. Trajectory Planning for Step Profile with and without the Inclusion of Efficiency in the Objective Function

Conclusions and Future Directions

Summary and conclusions of results obtained this year include:

- A thorough control design study resulted in a system design suited for control over a wide range of operating powers.
- Optimal input/output pairings for minimal interactions in a multi-loop feedback structure were identified via a relative gain array analysis.
- The feedback control structure was augmented by advanced control elements including feedforward look-up tables to ensure robust control in light of process uncertainty.
- The developed control system is capable of responding to rapid changes in load demand while simultaneously being able to reject disturbances in ambient temperature and fuel composition.
- The dynamic optimization framework facilitated studies of both power ramps at varying rates and stepping studies at various power levels while maximizing plant efficiency. This data will be utilized for neural network training.
- The optimization framework's applicability to parameter estimation and inferential control was demonstrated. Case studies, using the developed algorithms, verified that accurate estimation of variations in fuel composition is feasible, allowing for compensation of fuel flow and resulting in increased reliability of operation.

Overview of future work includes:

- Develop a centralized linear quadratic regulator including state estimation via Kalman filtering and determine whether it can improve robustness of the decentralized multi-loop controller.
- Develop a neural network framework suitable for online control supervision. Train the neural network with results from the control optimization studies.
- Develop fuzzy logic fault detection and fault accommodation techniques.
- Integrate the individual control strategies into the simulation environment for extensive testing of the algorithms for their stability and robustness.

FY 2006 Publications/Presentations

1. S. Kameswaran, D. Ko, L.T. Biegler, S.T. Junker, and H. Ghezel-Ayagh, *Optimal Off-Line Trajectory Planning for Load Ramping of Hybrid Fuel Cell/Gas Turbine Power Generating Plants*, AIChE Annual Meeting, Cincinnati, OH, November 2005.

2. *Advanced Control Modules For Hybrid Fuel Cell/Gas Turbine Power Plants,* DE-FG02-02ER86140, Semi-annual

Technical Progress Report No. 5, Reporting Period: 06-27-05 to 12-26-05, January 2006.

3. R.A. Roberts, J. Brouwer, F. Jabbari, S.T. Junker, and H. Ghezel-Ayagh, *Control Design of an Atmospheric Solid Oxide Fuel Cell/Gas Turbine Hybrid System: Variable versus Fixed Speed Gas Turbine Operation*, Accepted for Publication in the Journal of Power Sources, March 2006.

4. F. Mueller, F. Jabbari, J. Brouwer, R.A. Roberts, S.T. Junker, and H. Ghezel-Ayagh, *Control Design for a Bottoming Solid Oxide Fuel Cell Gas Turbine Hybrid System*, 4th ASME International Conference on Fuel Cell Science, Engineering and Technology, Irvine, CA, June 2006.

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1. S. Skogestad and I. Postlethwaite, *Multivariable Feedback Control – Analysis and Design*, John Wiley & Sons, New York, 1996.

2. S. E. Mattsson and G. Söderlind, *Index Reduction in Differential-Algebraic Equations Using Dummy Derivatives*, SIAM J. Sci. Comp. 14:677–692, 1993.

3. A. Wächter and L. T. Biegler, *On the Implementation of a Primal-Dual Interior Point Filter Line Search Algorithm for Large-Scale Nonlinear Programming*, Math. Program., 106: 25-57, 2006.